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Development of a smart docking system for small satellites

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Abstract. DOCKS is a smart docking system for space vehicles developed by the Department of Industrial Engineering, University of Padova, within the framework of the Space Rider Observer Cube (SROC) mission. The design and development of SROC is being conducted by a consortium of Italian entities under contract with the European Space Agency (ESA). The SROC mission is designed to be a payload on the ESA Space Rider (SR) spaceship. The main objective of the mission is to demonstrate the critical capabilities and technologies required to execute a rendezvous and docking mission in a safety-sensitive context. The space system is composed by a nanosatellite (approximately 12U CubeSat) and a deployment/retrieval mechanism mounted inside the payload bay of SR. During the mission, SROC will be released by SR, will perform inspection manoeuvres on SR and, at the end of the mission, will dock back inside the bay of SR, before re-entering Earth with the mothership. The docking functionality is provided by DOCKS. DOCKS is suitable for use onboard micro- and nanosatellites and merges a classical probe drogue configuration with a gripper–like design, to manage the connection between the parts. The system is equipped with a suite of sensors to estimate the relative pose of the target and with a dedicated computer, making it a smart standalone system. A laboratory prototype has been assembled and functionally tested, aiming at the validation of the capability to passively manage misalignments during the docking manoeuvre.

Introduction

The docking system (DOCKS) has been developed in the framework of the Space Rider Observer Cube (SROC) mission. The purpose of the mission is to demonstrate the capabilities and technologies required for rendezvous and docking with a target vehicle [1]. A brief description of the operations performed by SROC is:

1. Launch and early operations. SROC is stored inside the bay of Space Rider (SR). Once in orbit, SROC is pushed away from SR in order to begin its operative phases.
2. Proximity Operations. SROC is in a relative orbit with respect to SR in order to perform its observations.
3. Docking and Retrieval Phase. SROC approaches SR and docks with it in order to be re-stored inside the bay and return to Earth safely.

DOCKS overview

The DOCKing System (DOCKS) has been developed to be a standalone docking mechanism with an integrated set of sensors and a computer. In the following, all the parts of DOCKS will be described.

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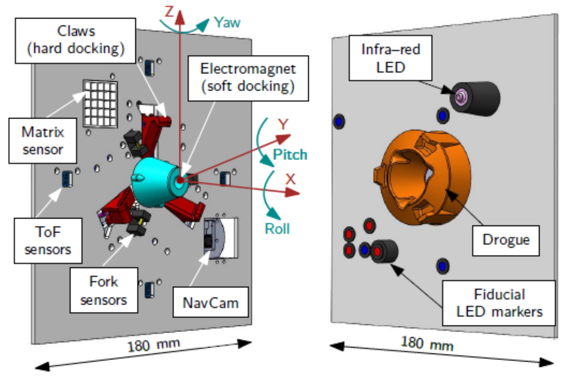

Figure 1: DOCKS-A and DOCKS-B. They are mounted on SROC and on SR respectively. In DOCKS-A it is also represented it frame of reference.

Docking mechanism

The mechanical connection between SROC and SR is provided by a docking mechanism that is composed by two main parts (Fig. 1). The first (DOCKS-A on SROC) is the active part with the mechanism, and the second (DOCKS-B on SR) is the counter part of the docking mechanism (the drogue) and the LEDs that allows the relative navigation.

The active part of docking mechanism is composed by two parts (shown in Fig. 2): a centring cone and three claws that provide the rigid mechanical connection.

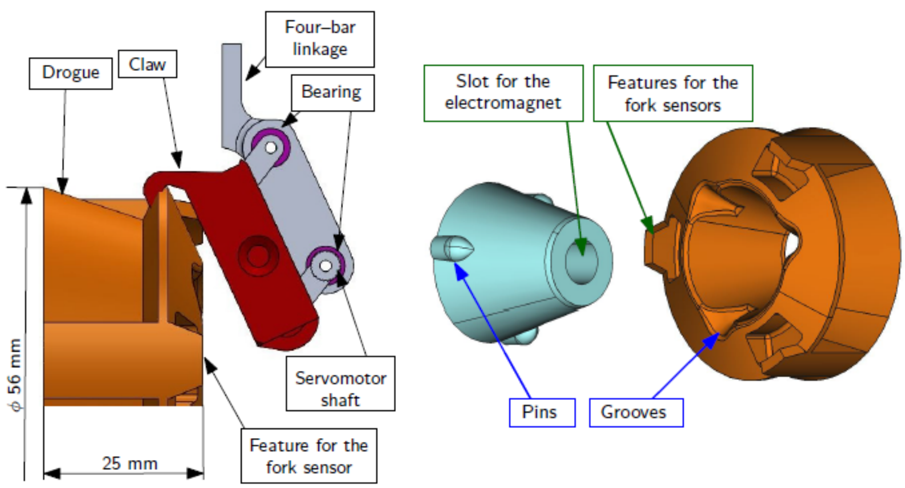

Figure 2: The centring cone and claws of DOCKS.

The centering cone has the purpose to force the alignment between SROC and SR when coupling with the drogue. In fact, the shape of the probe allows to tolerate 10 mm of lateral misalignment and 10 deg of pitch (and yaw) misalignment. In addition, the pins on the rim of the probe force the roll alignment, when they couple with the grooves on the drogue.

The hard docking is achieved with the three claws that ensure the rigid connection, by closing around the rim of the drogue. The claws are activated by a four-bar linkage in order to prevent linear actuations that could produce friction or jam the mechanism.

Sensor suite and estimation performances

As illustrated in Fig. 1, DOCKS-A is provided with three different sensors to measure the relative pose of DOCKS-B.

1. *A navigation camera*. Its purpose is to measure the entire relative pose of DOCKS-B. The NavCam with its computer, recognizes the pattern of LEDs on DOCKS-B and reconstruct its pose [2]. However, at distances lower than 50 mm, the camera is out of focus making the measurement unreliable.
2. *A set of four Time-of-Flight sensors*. They are employed to measure the distance and the relative pitch and yaw angles from 100 mm up to contact (as explained in Fig. 3) [3].
3. *A matrix sensor*. It is used to measure the relative position along the y and z axes (which is not measurable with the ToF sensors). The sensor employs a matrix of 5x5 phototransistors on DOCKS-A and an infrared LED on DOCKS-B. Depending on the relative position, the LED activates different pattern of phototransistors [4].

The ToF sensors are affected by a noise of approximately 4 mm at distances below 30 mm, causing an uncertainty on the measure of the relative angles of more than 5 deg. To improve the estimation, a Kalman filter has been applied to the measurements of the ToF sensors [5]. The tests performed on the sensor suite provided the estimation error reported in Tab.1.

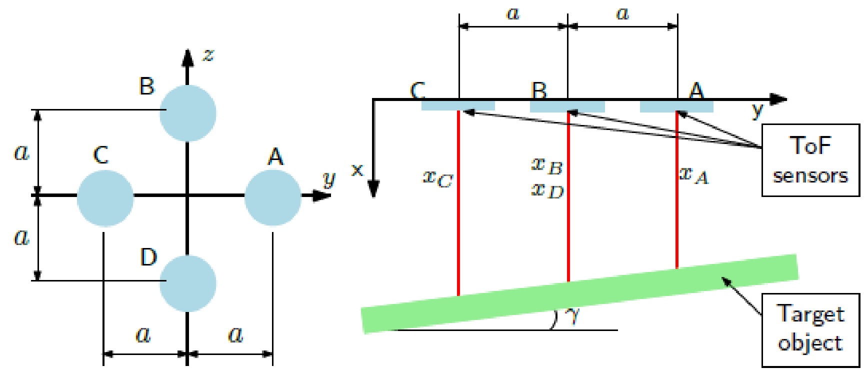

Figure 3: Measurement of the Time-of-Flight sensors.

Table 1: Estimation errors

	Error	X [mm]	Y [mm]	Z [mm]	Pitch [deg]	Yaw [yaw]
NavCam	Avg.	2.0	2.0	2.0	1.5	1.5
	Std. dev.	0.5	0.5	0.5	1.0	1.0
ToF + matrix	Avg.	0.14	1.16	1.41	0.52	0.11
	Std. dev.	0.43	0.13	2.13	0.64	0.68

Tests on DOCKS

DOCKS has undergone to a series of tests in order to verify its capabilities of DOCKS to tolerate relative misalignments and to self-align DOCKS-A to DOCKS-B. To this purpose, an ad-hoc experimental setup has been developed. DOCKS-A is mounted on the end-effector of a robotic arm, which has the purpose of moving DOCKS-A with an accuracy of 2 mm [6]. DOCKS-B is mounted on a frame DOCKS-B on a frame that blocks all the movements, except for the degree of freedom under tests for the self-alignment, as illustrated in Fig. 4.

At the beginning of the tests, the zero position has been defined as the perfect alignment between DOCKS-A and B. The tests have been conducted as follows: (1) a displacement has been imposed on DOCKS-B, (2) DOCKS-A has been moved along a linear trajectory to the zero position forcing the alignment between the parts. The test is considered successful if the claws close properly on the rim of the drogue without any residual displacement.

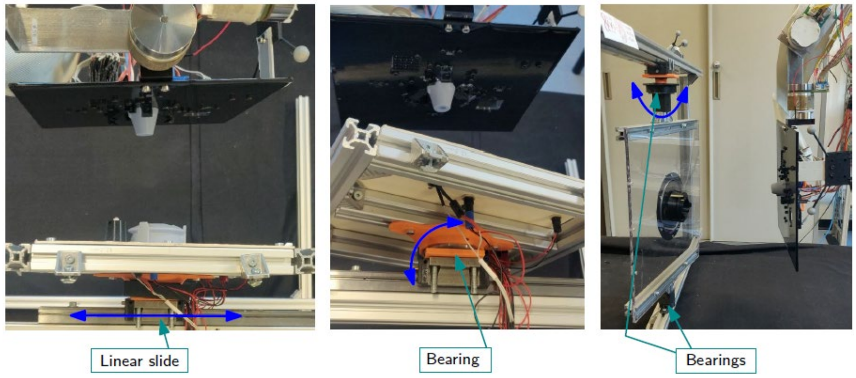

Figure 4: the experimental setups for the misalignment along the y axis, around the roll axis and around the yaw axis.

The results of the tests proved the capability of DOCKS to manage misalignment of 8.0 mm along the y and z axes, 9.0 deg around the yaw and pitch axes, and 10 deg around the roll axis.

Conclusions

This paper presents a brief description of an autonomous docking system, since it is equipped with (1) a set of sensors that, whith a Kalman filter, are able to estimate the relative pose of the target; (2) three actuators and an electromagnet to execute the soft and the hard docking; and (3) an integrated computer that applies the required algorithms to manage the sensors and actuators.

In addition, DOCKS has been designed to manage misalignment between DOCKS-A and DOCKS-B. To this aim, its centring cone with three features matches its counterpart on the target and forces the alignment between the parts. The test executed on DOCKS, proved that it is able to tolerate misalignment that are five to eight times the estimation errors of the sensors.

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